

# Corrosivity Testing and Intro to Corrosion Mitigation

RECLAMATION

# Your Friendly TSC Corrosion Staff:

**Daryl Little**  
Ph.D. Materials Science & Engineering  
[dlittle@usbr.gov](mailto:dlittle@usbr.gov)  
303-445-2384

**Lee Sears**  
Ph.D. Materials Science & Engineering  
[lsears@usbr.gov](mailto:lsears@usbr.gov)  
303-445-2392

**Jessica Torrey**  
Ph.D. Materials Science & Engineering  
[jtorrey@usbr.gov](mailto:jtorrey@usbr.gov)  
303-445-2376

**Roger Turcotte, PE, CPS**  
Materials Engineer  
[rturcotte@usbr.gov](mailto:rturcotte@usbr.gov)  
303-445-2383



Summer students: Marci Early, Grant Maloney, Kevin Pickard

# RECLAMATION

# Today's Topics:

## Corrosivity Testing of Soil and Water

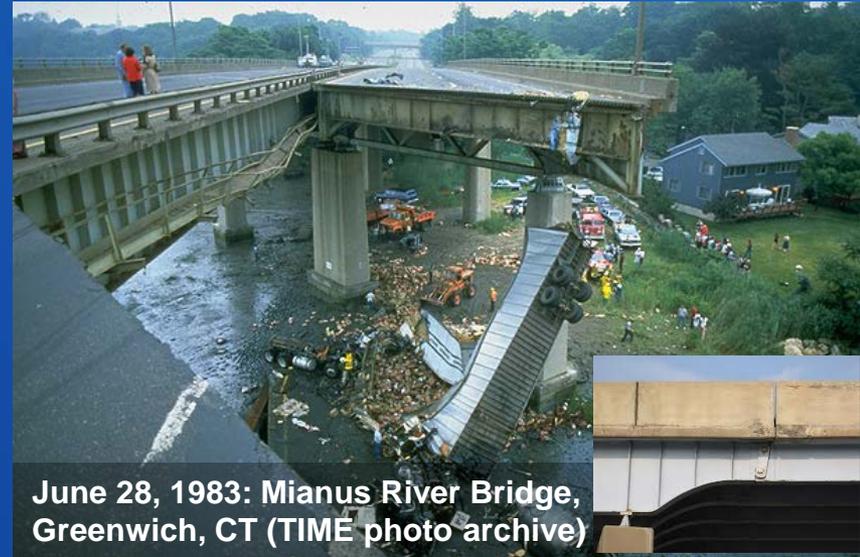
- pH, EC, Cl<sup>-</sup>, SO<sub>4</sub><sup>-2</sup>
- soil resistivity
- How do we use corrosivity testing to determine required corrosion mitigation?

## Corrosion Mitigation Methods

- Materials selection
- Protective coatings
- Corrosion Monitoring
- Cathodic Protection: Galvanic and Impressed Current

# Why is Corrosion Important?

**First and Most Important – Public Safety!**



June 28, 1983: Mianus River Bridge, Greenwich, CT (TIME photo archive)



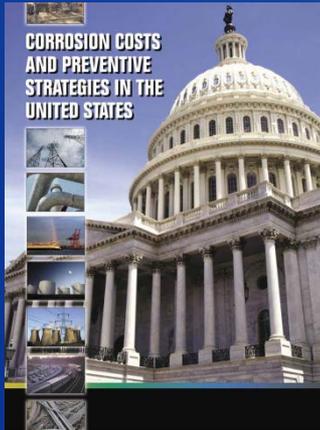
July 17, 1995, Folsom Dam, Spillway Gate No. 3



April 28, 1988, Aloha Airlines 737

**RECLAMATION**

# Why is Corrosion Important?



**Economic Costs:  
\$276 billion annually**

- “Corrosion Costs and Preventative Strategies in the United States,” Publication No. FHWA-RD-01-156, *NACE International and U.S. Federal Highway Administration*, 2002.
- Estimates economic impact of corrosion for specific industries and extrapolated to a national total
- Total *Annual* Estimated Direct Cost of Corrosion:
  - \$276 billion
  - ~ 3.1% of the country’s GDP
  - Indirect costs double that to \$552 billion or ~ 6% of the GDP

**RECLAMATION**

# Why is Corrosion Important?



- Report identifies several preventative strategies:
  - Increase awareness of corrosion costs and potential cost savings
  - **Change misconception that nothing can be done about corrosion**
  - Change policies, regulations, standards, and management practices to increase corrosion cost savings through sound corrosion management
  - **Improve education and training of staff in the recognition of corrosion control**
  - Implement advanced design practices for better corrosion management
  - Develop advanced life-prediction and performance assessment methods
  - Improve corrosion technology through research, development, and implementation

RECLAMATION

# What is Corrosion?

**CORROSION IS DEFINED AS THE  
DETERIORATION OF A MATERIAL AND/OR  
ITS PROPERTIES CAUSED BY A REACTION  
WITH ITS ENVIRONMENT.**

RECLAMATION

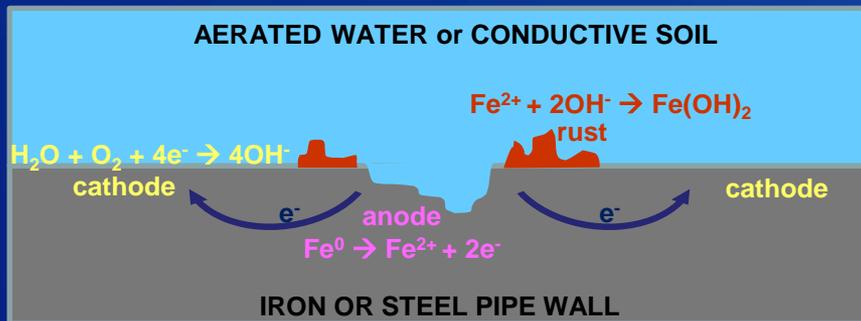
# The Corrosion Reaction

ex. oxidation, "rusting," electroplating, anodizing

## Electrochemical Reaction Between a Metal and an Electrolyte

ex. steel, copper, aluminum

ex. soil, water



Four Required Components for Corrosion:

1. Anode (Corrodes)
2. Cathode (Protected)
3. Electrolyte (Usually Soil or Water)
4. Metallic Return Path (ex. Pipe)

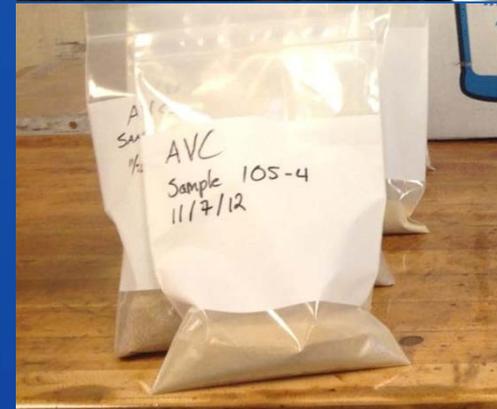
RECLAMATION

# Corrosivity Testing

RECLAMATION

# Soil and Water Corrosivity

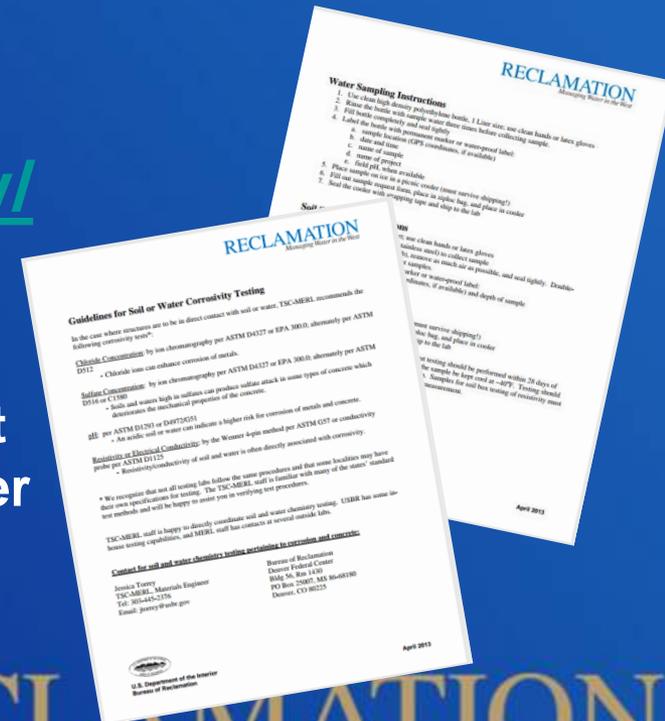
- In cases where a structure is going to be in direct contact with soil or water, corrosivity testing is recommended.
- Includes metallic and concrete structures.
- Corrosivity testing is used to help predict the likelihood of corrosion or degradation of a material in the sample environment.



RECLAMATION

# Soil and Water Corrosivity

- The TSC will request samples for corrosivity testing as part of a Field Exploration Request (FER).
  - If the testing is to be done by the Area Office, the request for corrosivity data will be included in the Design Data Request.
  - <https://sites.google.com/a/usbr.gov/corrosion/Resources>
- ## Guidelines for Corrosivity Testing
- outlines which test are requested, the test methods, and how to collect soil and water samples



# Corrosivity Tests- pH & EC

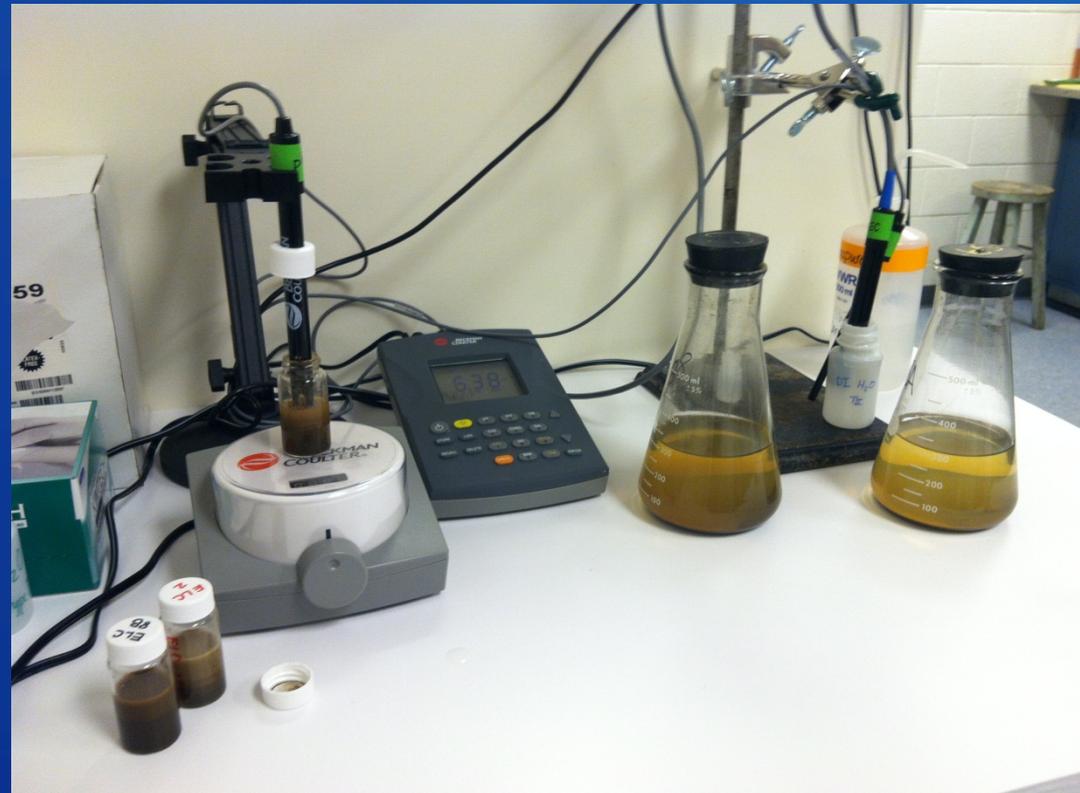
- pH

- An acidic soil or water can indicate a higher risk for corrosion of metals and concrete
- Per ASTM D1293 or D4972/G51



- Electrical Conductivity (EC)

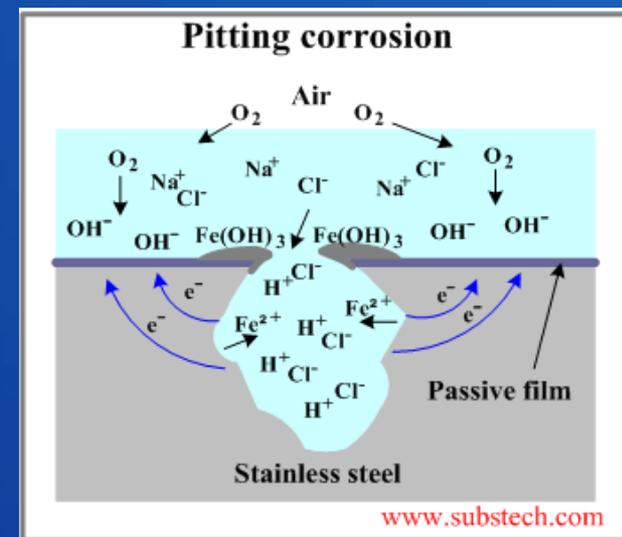
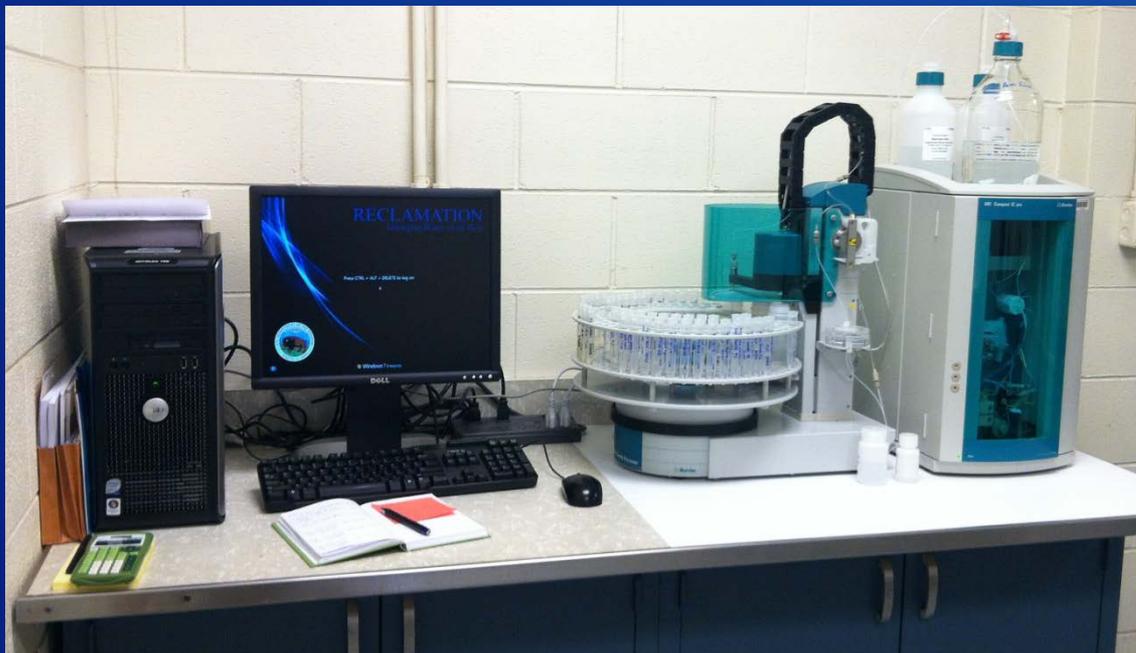
- The conductivity of soil and water is often directly associated with salt concentration and corrosivity
- With conductivity probe per ASTM D1125 and ASA #9-2 Method 10-3.3



# Effect of Cl<sup>-</sup> on Corrosion of Metals

- Chloride Concentration Test (Cl<sup>-</sup>)

- Chloride ions can enhance the corrosion of metals
- In the presence of chlorides, pitting corrosion can be greatly accelerated
- Chloride ions are also major cause for corrosion of steel reinforcement in concrete
- Exposure to chlorides can come from the environment (soil, water) but also through exposure to deicing salts
- Tested by ion chromatography per ASTM D4327 or EPA 300.0; alternately per ASTM D512



# Effect of $\text{SO}_4^{-2}$ on Degradation of Concrete

- **Sulfate Concentration Test ( $\text{SO}_4^{-2}$ )**
  - Soils and water high in sulfates can produce sulfate attack in some types of concrete which deteriorates the mechanical properties of the concrete
  - Sulfate attack causes loss of cohesion between the cement and aggregate and ultimately loss of strength in the concrete
  - Tested by ion chromatography per ASTM D4327 or EPA 300.0; alternately per ASTM D516 or C1580

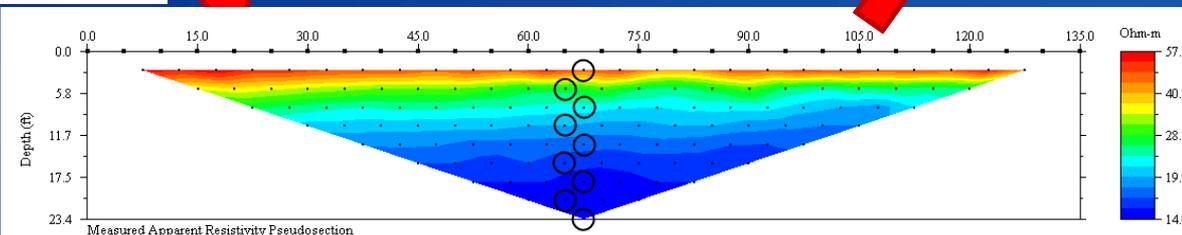
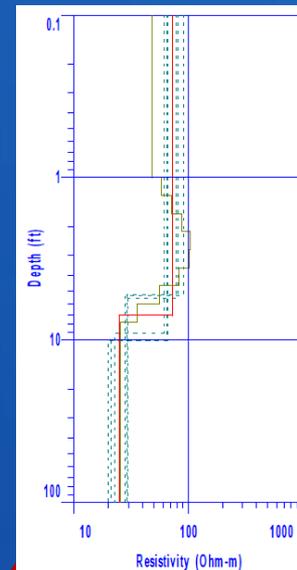
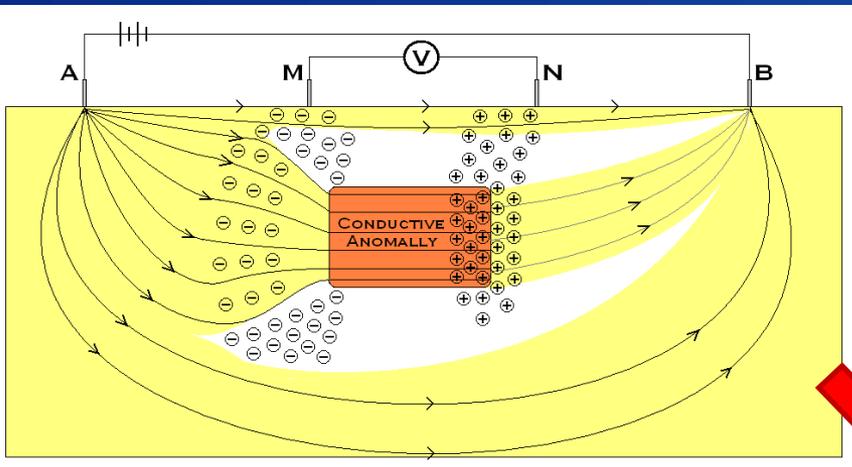


From PCA "Design and Control of Concrete Mixtures" 2011

# Soil Resistivity Testing

- **Soil Resistivity- Wenner 4-Pin Method**

- Four pins are inserted into the ground in a straight line, equally spaced
- Current is passed through the subsurface soil between the outer two pins and voltage is measured on the surface between the two inner electrodes
- A 2D cross-section of apparent resistivity is measured and processed to a 1D inversion model of true resistivity as function of depth
- Soil Resistivity is organized through the Geophysics Group at TSC
- A laboratory Soil Box Method (ASTM G57) can be performed at MERL



# Soil Resistivity Testing



# How do we use this data?

- Measured values are compared to published guidelines
- Recommendations are made to consider corrosion mitigation measures or special concrete mix design
  - Ex: “Severe” Sulfate Concentration → use a low water-cement ratio, Type V cement, and silica fume/ fly ash/ slag

	Low Sulfate Content (<1000 ppm)
	Moderate (1000-2000 ppm)
	Severe (2000-20000 ppm)
	Very Severe (>20000 ppm)
	Moderate Chlorides (>100 ppm)
	High Chlorides (>500 ppm)
	pH<6, pH>9

Pipe Alternative	Soil Resistivity – 10% Probability Value (ohm-cm)	Minimum External Protection (Primary/Supplemental)	Corrosion Monitoring	Cathodic Protection <sup>2</sup>
Ductile Iron	≤ 2,000 ohm-cm	Bonded dielectric <sup>3</sup>	YES	YES
	> 2,000 ohm-cm < 3,000 ohm-cm	Polyethylene encasement	YES	YES
	≥ 3,000 ohm-cm	Polyethylene encasement	YES	NO
Pretensioned Concrete	<3,000 ohm-cm	Mortar / coal-tar epoxy	YES	YES
	≥3,000 ohm-cm	Mortar	YES	NO
Reinforced Concrete	< 3,000 ohm-cm	Concrete / coal-tar epoxy	YES	YES
	≥3,000 ohm-cm	Concrete	YES <sup>4</sup>	NO
Steel	≤ 2,000 ohm-cm	Bonded dielectric <sup>3</sup>	YES	YES
	> 2,000 ohm-cm < 3,000 ohm-cm	Mortar / coal-tar epoxy	YES	YES
	≥3,000 ohm-cm	Mortar	YES	NO

<sup>1</sup> This table should be considered to be the minimum corrosion prevention requirements for a pipeline corrosion design. Additional soil conditions and risk assessment factors should be considered on a case-by-case basis for each specific project.  
<sup>2</sup> OMR&E costs for cathodic protection for each pipe type should be evaluated.  
<sup>3</sup> Bonded directly to metal to be protected.  
<sup>4</sup> Corrosion monitoring is required for concrete pipe with steel joint rings, but not for concrete pipe with concrete joints.]

Table 3-2. Types of Cement Required for Concrete Exposed to Sulfate in Soil or Water\*

Exposure class		Sulfate exposure**		Cementitious materials requirements†			Maximum w/cm
		Water-soluble sulfate in soil, % by mass	Dissolved sulfate in water, ppm	C150	C595	C1157	
S0	Negligible	SO <sub>4</sub> < 0.10	SO <sub>4</sub> < 150	NSR	NSR	NSR	None
S1	Moderate‡	0.10 < SO <sub>4</sub> < 0.20	150 < SO <sub>4</sub> < 1500	II or II(MH)	IP(MS) IS(< 70)(MS) IT(P ≥ S)(MS) IT(P < S < 70)(MS)	MS	0.50
S2	Severe	0.20 < SO <sub>4</sub> < 2.00	1500 < SO <sub>4</sub> < 10,000	V	IP(HS) IS(< 70)(HS) IT(P ≥ S)(HS) IT(P < S < 70)(HS)	HS	0.45
S3§	Very severe	SO <sub>4</sub> > 2.00	SO <sub>4</sub> > 10,000	V	IP(HS) IS(< 70)(HS) IT(P ≥ S)(HS) IT(P < S < 70)(HS)	HS	0.40

# Corrosion Mitigation Methods

- **Materials selection**
- **Protective coatings**
- **Corrosion Monitoring System**
- **Galvanic Anode Cathodic Protection**
- **Impressed Current Cathodic Protection**

# Design Considerations for Corrosion Mitigation

**\*\* Unlike oil and gas industry, water industry is not required by law to apply cathodic protection to its structures. Therefore, we need good data and engineering practice to make informed design decisions.**

- **Nature of Electrolyte:**
  - results of corrosivity testing
- **Structure details**
  - type, shape, size
- **Good Engineering Practice**
  - ex.- History of Other Proximate Structures
- **Requests from Client**

East Low Canal Siphon, 2010



# Materials Selection

RECLAMATION

# Importance of Materials Selection

- **Some materials inherently resist corrosion**
- **The proper choice of materials can result in:**
  - Longer service life
  - Little or no maintenance requirements
  - \$\$\$ saved
  - Lower risk of catastrophic failure and risk to public
- **Materials selection is application and environment specific and should be done on a case-to-case basis**
- **There are considerations in addition to corrosion resistance, examples:**
  - Strength
  - Flammability
  - Fabricability

# Classes of Materials

Metals	Ceramics	Polymer	Composites
Ex. steel, iron, aluminum, graphite	Ex. quartz/SiO <sub>2</sub> , Al <sub>2</sub> O <sub>3</sub> , SiC, porcelain	Ex. PVC, HDPE, nylon, teflon	Ex. reinforced concrete, fiber reinforced polymers
 	 	 	 

# Factors Influencing Materials Selection

- **Performance requirements for intended application**
- **Working environment (corrosivity)**
- **Cost**
- **Installation flexibility**
- **Availability/ Sourcing**
- **Maintenance requirements/ Maintainability**
- **Compatibility with other system components**
- **Appearance**
- **Client Preference**

# Galvanic Couples

**Two things to note when choosing a metal:**

- location in galvanic series- anodic or cathodic metal?
- is the metal *passivated* or not?
  
- Use alloys with similar potentials
- Electrically isolate different metals or active vs. passive metals
- Maximize anode to cathode surface ratio
  - Coat the noble metal (i.e. the cathode)
  - Make certain that the smaller part is the cathode in the couple
- Cathodically protect

# Protective Coatings

RECLAMATION

# Protective Coatings

“The total annual U.S. cost for organic and metallic protective coatings is \$108.6 billion. 50% of all corrosion costs are preventable, and approximately 85% of these are in the area of coatings.” -NACE website, 2013

Protective coatings (including paint) are the primary means employed by Reclamation to control corrosion.

The most important aspect to achieving a good coating is proper surface preparation.



RECLAMATION

# Protective Coatings

## Three Types of Materials for Protecting Metals:

- **Inhibitive-** pigment in coating is slightly water soluble and forms a chemical inhibitor to interfere with the electrolyte
  - Out of date: Chromate, Red Lead
  - Current: Phosphates, Zinc oxide, Molybdate
- **Barrier-** forms a barrier between metal and electrolyte and electrically isolates metal
  - Epoxies, Coal Tar Epoxies, Aromatic Polyurethanes
- **Sacrificial-** provide galvanic protection to ferrous metal via coating with a more reactive metal
  - Zinc rich coatings
  - Galvanizing
  - Metallizing

# Coating Selection

## Immersion:

- Epoxies & Coal Tar Epoxies
- Moisture Cured Polyurethanes and Siloxane
- Fusion Bonded Epoxy (for small parts only)
- Nylon, PVDF, Teflon (for small parts only)

## Buried Applications:

- Epoxies & Coal Tar Epoxies

## Atmospheric Corrosion:

- Aliphatic Polyurethanes, Alkyds, & Acrylics
- Moisture Cured Polyurethanes and Siloxane (RH= 30-100%)
- Zinc Rich Coatings (no CP!, good under low water/ RH)
- Nylon, PVDF, Teflon (for small parts only)

## Many Applications:

- Polyureas, 100% Solids Epoxy, and Aromatic Polyurethanes (Plural Component)

RECLAMATION

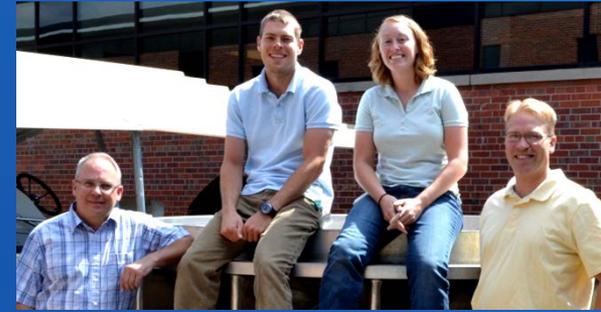
# Protective Coatings



Coating repair vs. unrepaired section, Seminole Dam Gate, 2012



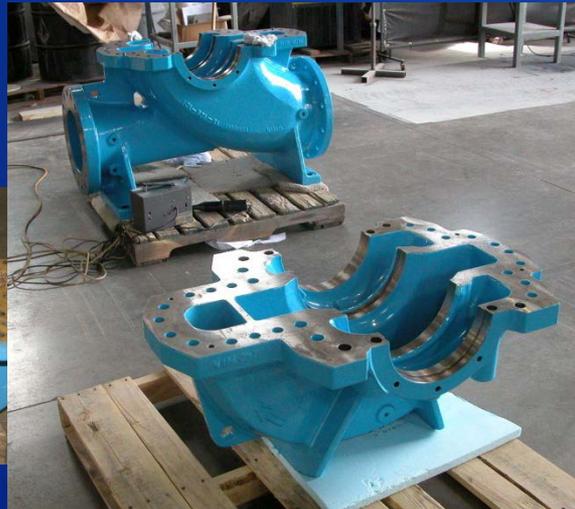
Galvanized and



Trashrack- Parker Dam, 2012



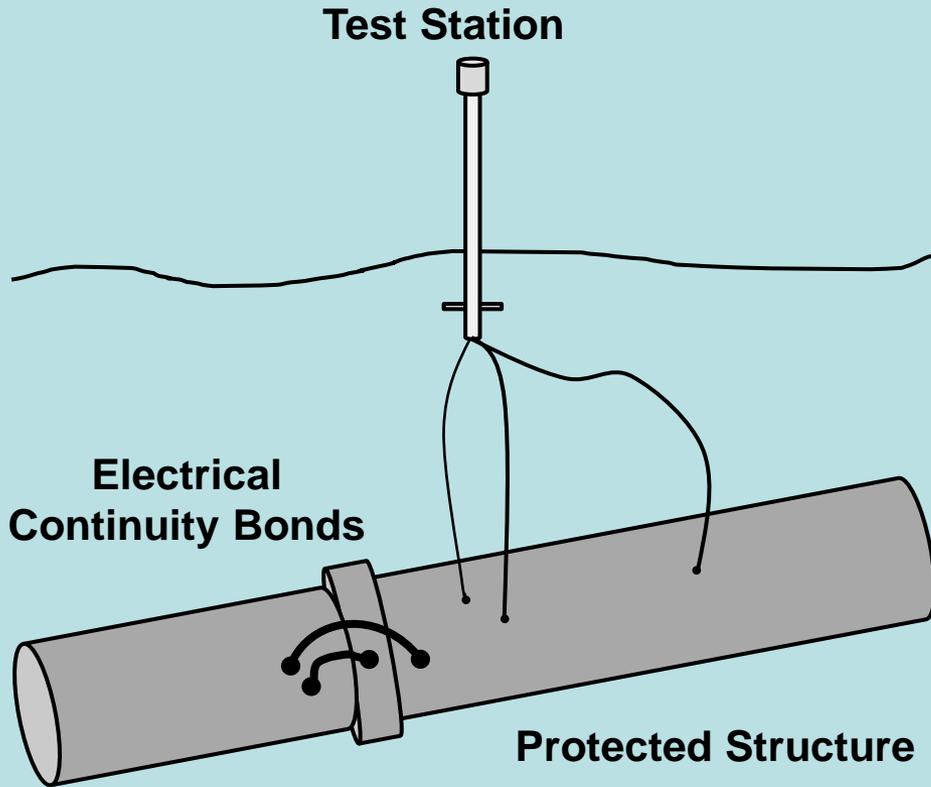
Damaged and Repaired Pump Coatings, Durango Pumping Plant, 2011



# Corrosion Monitoring System

RECLAMATION

# Corrosion Monitoring System



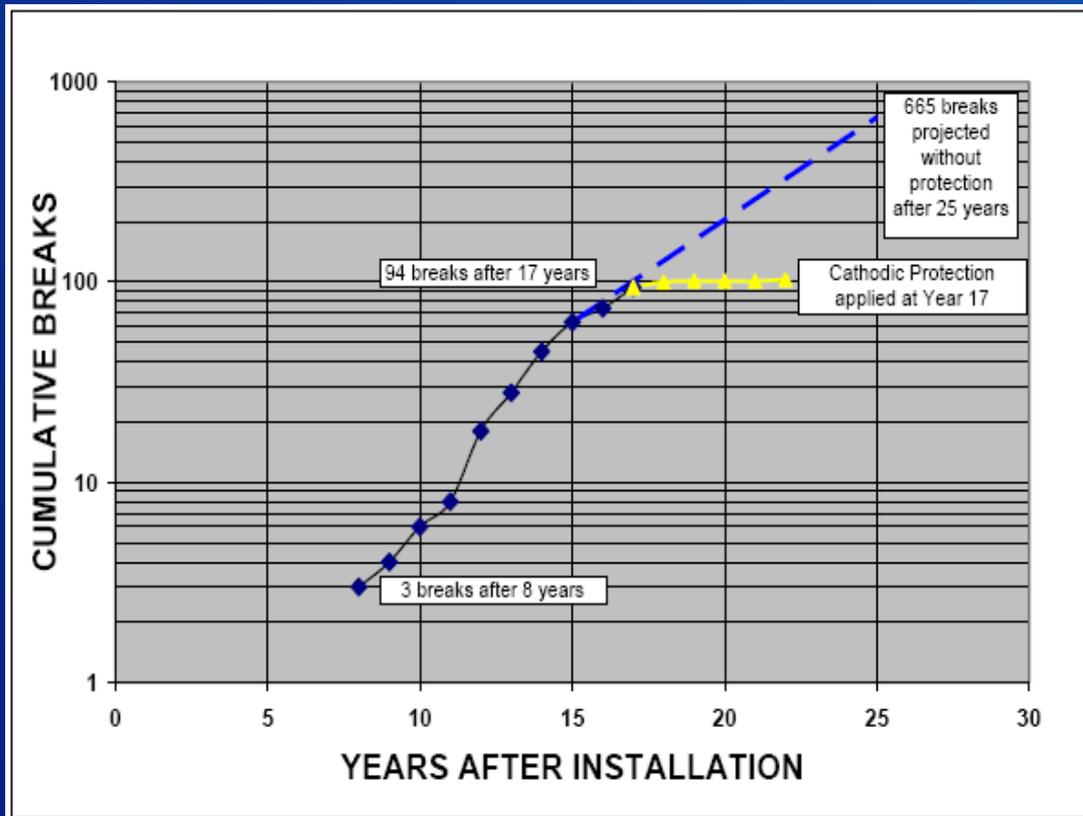
RECLAMATION

# Corrosion Monitoring System

- **Consist of electrical continuity bonds between structures to be monitored (i.e., pipe sections)**
- **Monitoring functionality is included in design of many CP systems**
- **Monitoring Systems alone can also be installed in cases of:**
  - **Corrosive soils but non-corrosive history of existing structures**
  - **Borderline corrosive soils**
  - **Areas with extreme wet-dry cycles**

# Corrosion Management Programs

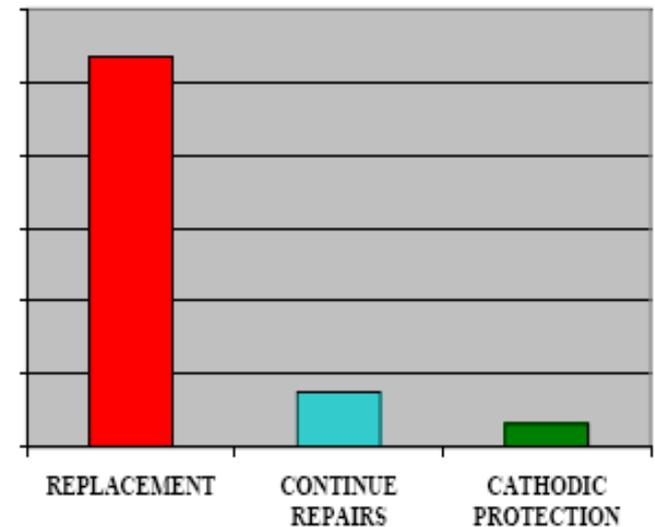
## Effectiveness of Well Designed Program



## Economic Benefits

Annualized Costs – 20 Yr. Cycle

Life Extension Cathodic Protection 58% less expensive than continuing with repairs



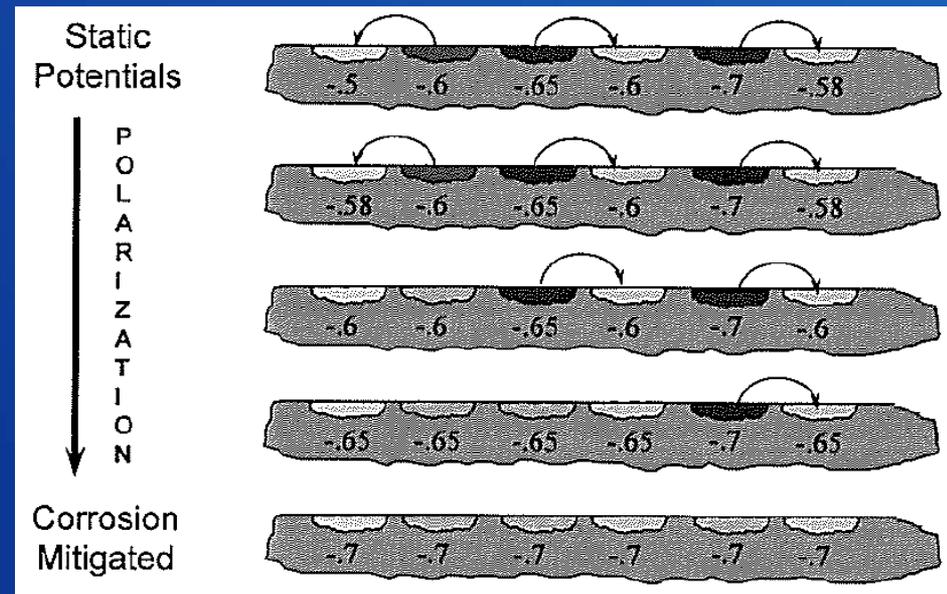
RECLAMATION

# Cathodic Protection

RECLAMATION

# Cathodic Protection

- Direct Current Flows Through the Electrolyte From Anode to Structure
  - Polarizes Structures to Eliminate Potential Differences Between Anodic and Cathodic Area
  - Corrosion Rate Ceases or is Greatly Reduced
- Electrons are provided from a source outside the structure.
  - Via a more active metal to be sacrificed.
  - Via a rectifier.
- Normally, the surface is coated to reduce current requirements and to better distribute the current.

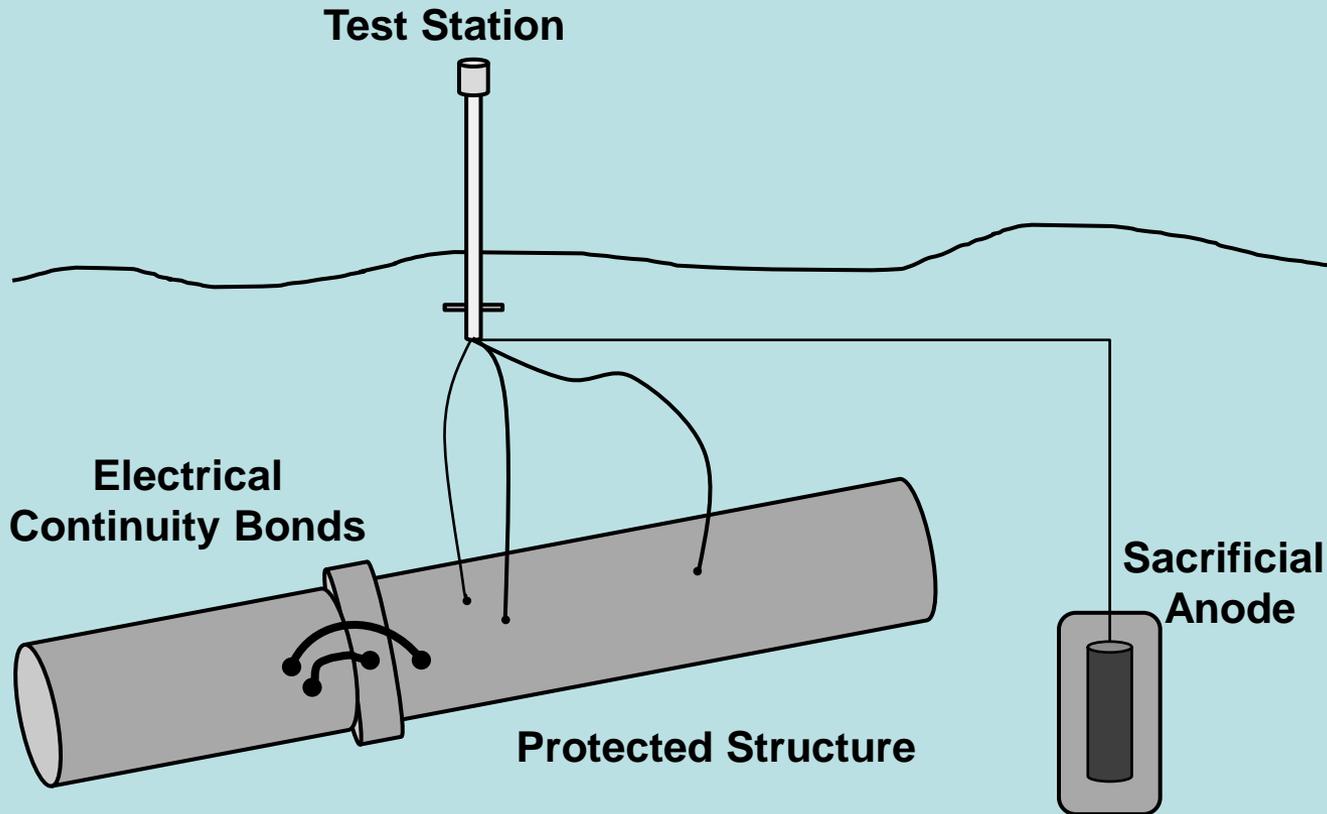


# Two Forms of Cathodic Protection

- **Galvanic**
  - Structure Metallurgically Bonded to an Anode
  - Current Provided by Natural Potential Difference Between Metals
- **Impressed Current**
  - Current Supplied by Outside Source

# Galvanic CP System

San Xavier Farm Rehabilitation,  
July 2007



RECLAMATION

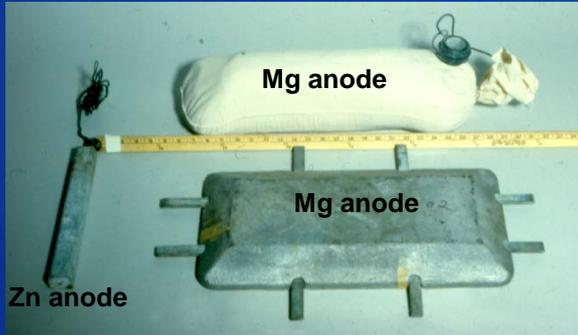
# Galvanic CP System



- Also known as **Sacrificial Anode Cathodic Protection**
- This system provides a cathodic current by galvanic corrosion or by sacrificing one material to prevent corrosion of the other material
- Both the structure and the anode must be in contact with the electrolyte



# Galvanic CP System



## Anodes:

- Soil and Fresh Water- Magnesium and Zinc
- Brackish Water- Aluminum and Zinc

## Applications:

- Pipelines, Fittings, and Valves
- Trashracks
- Hotspot Protection
- Gates
- Tanks
- Stray Current Interference Mitigation

## Requirements:

- Low current requirements
- Typically smaller surface area



New Mg Anode



Old Mg Anodes



RECLAMATION

# Pros and Cons of GACP



## Pros:

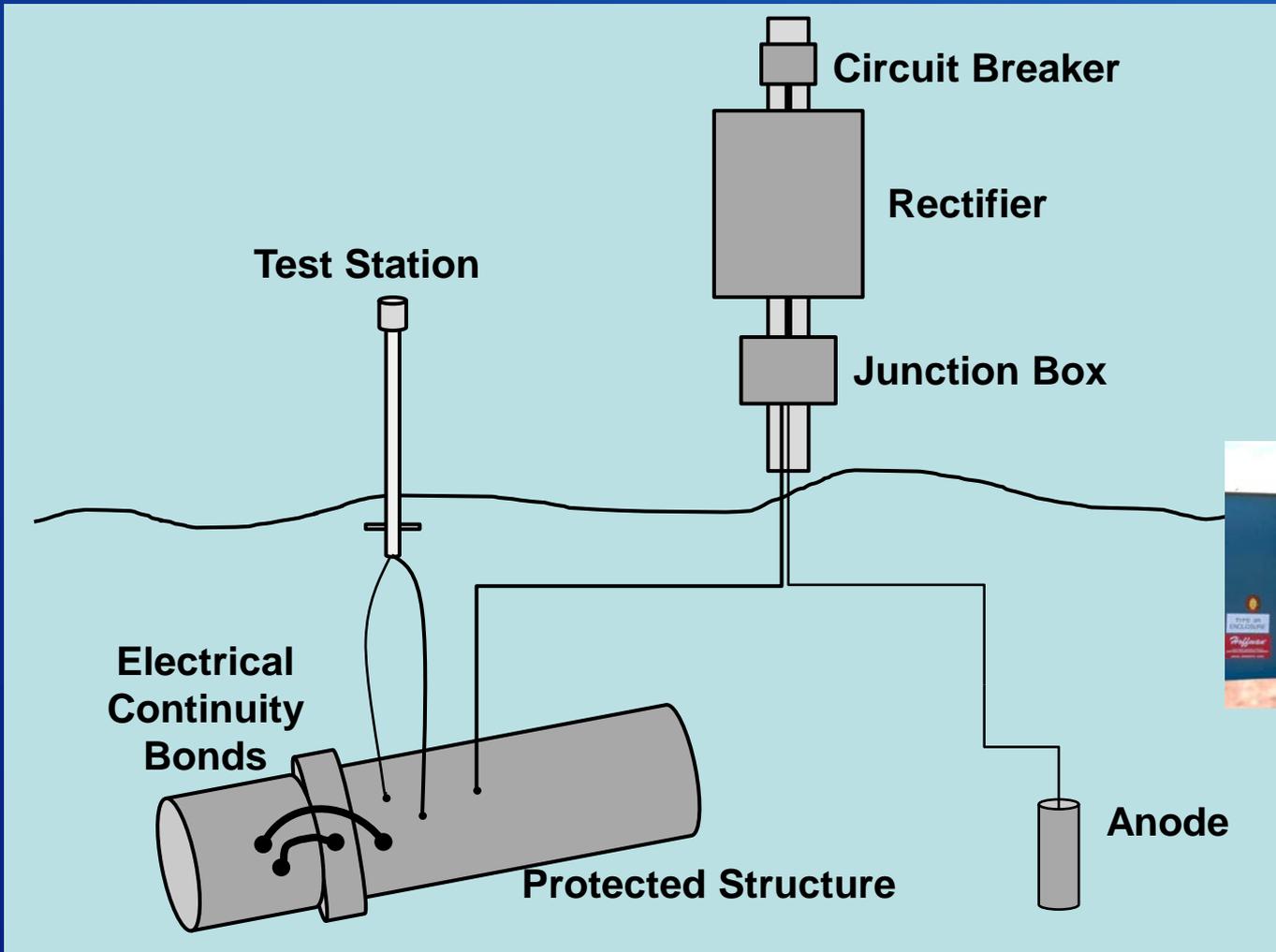
- No external power needed
- Easy to install
- Low maintenance
- Uniform distribution of current
- More anodes can be added if needed
- Minimum right-of-way required



## Cons:

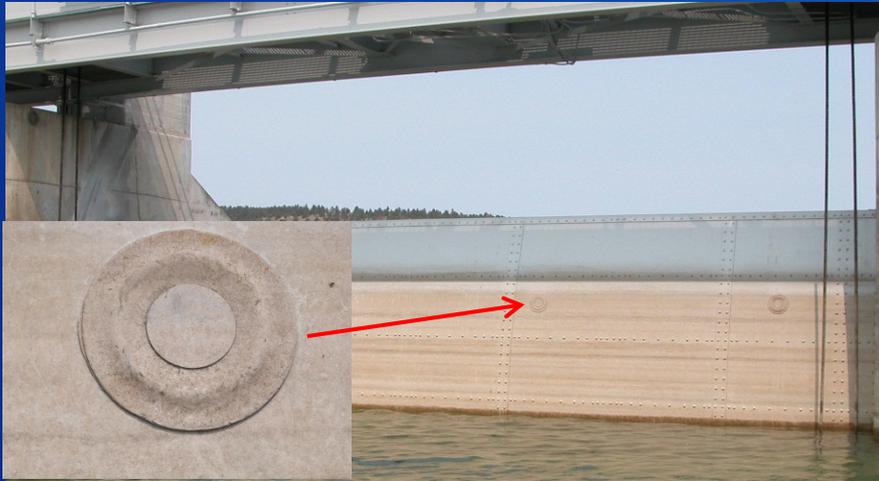
- Limited driving potential / current output
- Effectiveness depends on coating quality
- May be ineffective in high resistivity soils
- Higher cost per amp than impressed current

# Impressed Current CP System



RECLAMATION

# Impressed Current CP System



Mixed Metal Oxide Disk Anode



Angostura Dam Radial Gates, May 2004

- This system provides a cathodic current from an external power source
- A direct current power source forces current to discharge from anodes, through the electrolyte, an onto the structure to be protected
- Both the structure and the anode must be in contact with the electrolyte

# Impressed Current CP System

## Graphite Anodes



## High-Si Cast Iron Anode



Farwest Corrosion Control Company

## Anodes:

- Graphite, High-Si Cast Iron, Mixed Metal Oxide, Platinum, etc.
- Anodes Normally Connected Through Calibrated Shunts in Junction Box
- Installed via Linear or Deep Anode Ground Beds

## Applications:

- Pipelines
- Reinforced Concrete
- Pumping Plant Pump Sumps
- Trashracks
- Tanks
- Gates

## Requirements:

- High current requirements



CP System on Pump Columns in Sump

# RECLAMATION

# Pros and Cons of ICCP



## Pros:

- Flexibility to handle high voltage / current requirements
  - large structures can be protected
  - poorly coated structures can be protected
- More effective in high resistivity soils
- One anode bed can supply large amount of current
- Virtually no auto-corrosion of anodes



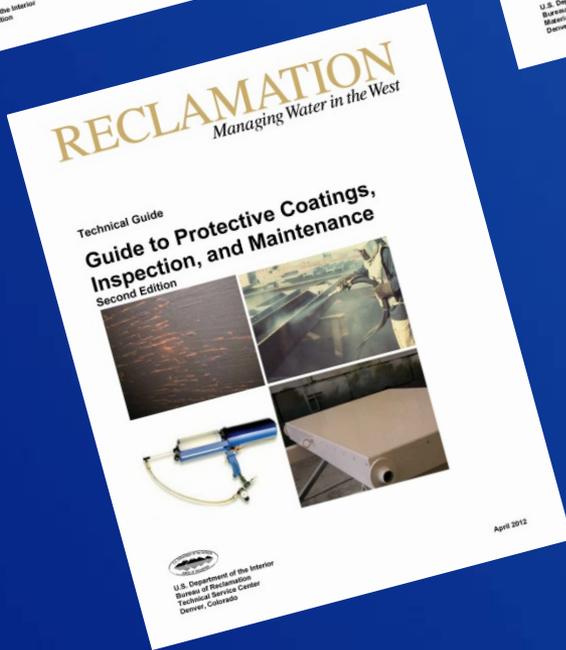
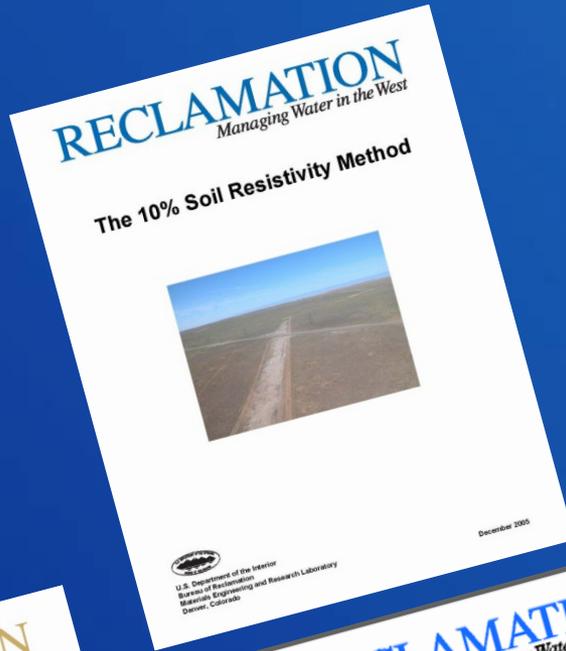
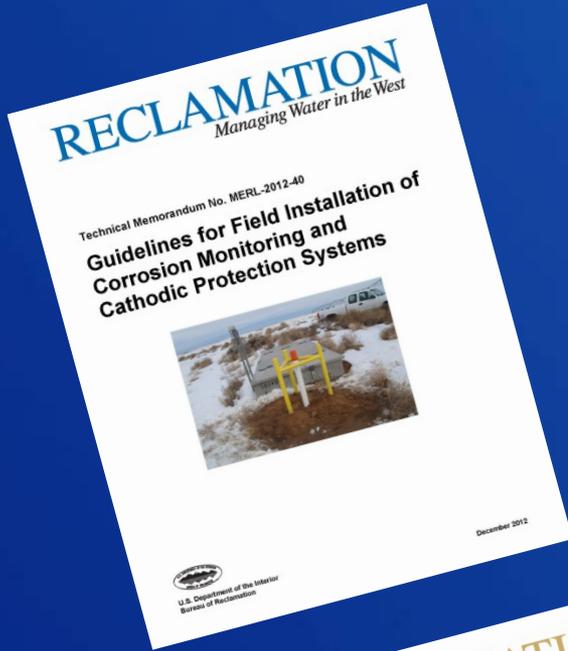
## Cons:

- Requires outside current source
- Can require a larger right-of-way for installation
- Installation can be more difficult (deep wells)
- System is more expensive to install and operate (cost of power, etc.)
- Requires more maintenance (protection level adjusting, equipment, etc.)
- Risk of stray current interference on foreign structures

# Corrosion Protection

The most effective corrosion protection system for buried and submerged structures involves a **good bonded coating** and **cathodic protection**.

# Coatings and Corrosion Manuals



**RECLAMATION**

# Upcoming Events

- **Corrosion and Coatings School**
  - October 22-24, 2013
- **Corrosion Website Update**
  - Summer 2013
- **Next Corrosion Webinar:**
  - Tentative: October 2013/ February 2014
  - “Cathodic Protection- System Components and Testing”
  - What do you want to hear about? Please suggest topics for future webinars!

# Coatings & Corrosion School Topics

- I. Introduction to Corrosion
- II. Materials Selection
- III. Introduction to Protective Coating
- IV. Surface Preparation
- V. Handling and Disposal of Coatings Containing Hazardous Waste
- VI. Coatings Technology
- VII. Coatings Application
- VIII. Coatings Surface Preparation and Application (Hands-on)
- IX. Inspection of Coatings
- X. Use of Inspection Equipment (Hands-on)
- XI. Inspection of Aging Infrastructure
- XII. Common Design Flaws
- XIII. Corrosion Mitigation Methods
- XIV. Solutions to Common Problems
- XV. Over coating
- XVI. Metallizing
- XVII. Corrosion Protection Safety
- XVIII. Corrosion Evaluation Test Equipment
- XIX. Cathodic Protection System (Hands-on)
- XX. Coatings for Concrete
- XXI. Current Research Activities
- XXII. Zebra and Quagga Mussels

RECLAMATION

# Questions? Comments?

**Daryl Little**

**Ph.D. Materials Science & Engineering**

**[dlittle@usbr.gov](mailto:dlittle@usbr.gov)**

**303-445-2384**

**Lee Sears**

**Ph.D. Materials Science & Engineering**

**[lsears@usbr.gov](mailto:lsears@usbr.gov)**

**303-445-2392**

**Jessica Torrey**

**Ph.D. Materials Science & Engineering**

**[jtorrey@usbr.gov](mailto:jtorrey@usbr.gov)**

**303-445-2376**

**Roger Turcotte, PE, CPS**

**Materials Engineer**

**[rturcotte@usbr.gov](mailto:rturcotte@usbr.gov)**

**303-445-2383**



**RECLAMATION**